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TWO-DIMENSIONAL DIFFUSION CALCULATIONS ON CO-AXIAL CAVITY REACTORS

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Introduction

In the last few years there have been an increasing number of ideas and schemes on the retention of gaseous nuclear fuel in a cavity reactor. Some methods proposed make use of hydrodynamic forces, such as the vortex type discussed by Kerrebrock and Meghreblian[1], and the coaxial flow type described by Weinstein and Ragsdale[2]. Other methods require magnetic forces to contain the fuel in the cavity, such as proposed by Spencer[3] and Nelson[4]. There have been other proposals with variations on these methods. With the exception of the vortex type, one common requirement imposed on the fuel is that it be centrally located, away from the cavity walls. In an arrangement such as this, it is expected that the critical mass requirements will be higher than that of a uniformly filled cavity.

In a previous analysis on spherical geometries[5], this increase in critical mass was indicated as being less than 25 percent for fuel-to-cavity radius ratios down to 0.5, for cavity radii ranging from 70 to 175 cm. In a cylindrical cavity reactor the fuel would be centrally located only with respect to the radius. As shown in figure 1, the fuel region runs the entire length of the cavity. It is anticipated that this would allow a further decrease in the fuel-to-cavity radius ratio without an increase in the critical mass.

Conditions of Analysis

The moderator-reflector region, as shown in figure 1, completely surrounds the cavity. The thickness of this region is maintained at 100 cm for all calculations. Graphite and D_2O were considered as moderator materials; and U^{235} and Pu^{239} as nuclear fuels. The radius of the cavity was varied in a few cases, but for the majority of the computations was held constant at 150 cm, along with a reactor cavity L/D (length-to-diameter) ratio of 1.0.

The cavity radius was chosen on examination of the combined continuity equations for the propellant (hydrogen) and the fuel (uranium or plutonium), expressed as a velocity ratio in a coaxial flow reactor[2]:

$$\frac{u_{H_2}}{u_F} = \frac{(w_{H_2}/w_F)(M_F/M_{H_2})(t_{H_2}/t_F)}{\left(\frac{1}{r_F/r_{H_2}}\right)^2 - 1}$$

To minimize mixing losses it is assumed that the average velocity ratio must be on the order of 100 or less. With the mass flow, molecular weight, and temperature ratios relatively invariant, the radius ratio r_F/r_{H_2} becomes the dominant factor. Small radius ratios ease the hydrodynamic restrictions on the velocity ratio required, but lead to high operating pressures because of the increase in critical densities. Combining these factors, a value of 150 cm was assumed for a reasonable cavity radius, and 0.17 for a fuel-to-cavity radius ratio. Inasmuch as these are only guesses as to reasonable values, they should not be taken as final or recommended values; they are, however, suitable for discussion here.

To determine the effect of changing radius ratio on criticality, the fuel region radius was varied and critical densities were obtained. The region of the cavity outside of the fuel region contained hydrogen with a density of 0.8×10^{21} atoms/cc. Although diffusion of neutrons in the hydrogen was considered, removal and absorption cross-sections were taken as zero. All of the results presented here were based on calculations of criticality obtained with PDQ02, a two-dimensional reactor code written[6] for the IBM 704. Neutron macroscopic cross sections for the materials were basically obtained by flux weighting cross sections from BNL 325[7]. For the high temperature "thermal" cross sections, the effect of Doppler broadening was taken into account. This was done primarily because of low energy level resonances in plutonium and uranium. For a given geometry the fuel density was varied until a criticality factor of 1.00 was obtained.

Discussion of Results

In general cavity reactors are considered thermal in the sense that most of the absorptions of neutrons by the fuel occur at thermal energies. In a cavity reactor the neutrons are born in the fuel at high energies and quickly diffuse into the reflector-moderator region. Here they are thermalized and find their way back into the fuel region to be absorbed and start a new generation of neutrons. As the fuel region is decreased in diameter, the probability that returning neutrons will ~~pass through~~ intersect it ~~again~~ is reduced. Therefore, to maintain criticality the ones which do pass through the fuel must have a higher probability of being absorbed. This means that as the fuel radius is decreased, the fuel density must increase. As the fuel density increases, the thermal flux drops off more rapidly through the fuel region. An example of this is shown in figure 2. For three different fuel radii, the flux drops off more rapidly as the fuel radius is decreased, and the fuel density is increased to maintain criticality.

Since the fuel volume is decreasing, an increase in fuel density does not necessarily mean that the critical mass has increased. Several configurations were computed to determine the effect on critical mass as the fuel radius is decreased. This is indicated in figure 3. The lower curve is for a cavity radius of 40 cm, and L/D of 2, and illustrates that, based on diffusion theory, the fuel region can be reduced in radius by factors of 5 and 6 with no appreciable increase in critical mass.

The remaining curves are for a cavity radius of 150 cm. The dashed line extensions are extrapolations to end points (cavity completely filled with fuel). The end points for the D_2O cases were determined from a buckling analogy[5]. All of the curves for U^{235} indicate that the fuel radius can be reduced by factors of 5 or 6, that is, fuel-to-cavity radius ratios of 0.2 to 0.167, without increasing the critical mass by more than 25 percent. The curve for Pu^{239} fuel indicates a sharp increase in critical mass at a radius ratio of about 0.25, or a factor of 4 in decreased radius. Although this is less of a reduction in fuel radius than afforded by the U^{235}, the critical mass is much less (10 kg compared with 30 kg at 0.4 radius ratio) under the same conditions.

As was previously indicated, a fuel radius of 25 cm appears to be in the region of interest. Maintaining this fuel radius and a cavity radius of 150 cm, several calculations were performed to determine changes in critical mass due to variations in temperature and materials. The results are shown in table 1. Case (1), as shown in the table, had U^{235} as the fuel, and D_2O as the moderator (100 cm thick). Since D_2O was used, the neutrons were assumed to be at room temperature (70° F). The critical mass for this case is seen to be 6.3 kg. In the next case, as shown in the diagram with table I, a void region through the D_2O with the same diameter as the fuel region was added to one end to obtain some indication of the effect of an exhaust nozzle; the increase in critical mass was small (5 percent).

In the third case, the D_2O was replaced with graphite. The increase in critical mass from 6.3 to 65 kg is due primarily to the increased absorption in the graphite moderator, as is shown in table II. Therefore, an increase in the thermal temperature to near an operating temperature (approximately 5300° F) should decrease the critical mass. This is shown by the results for case 4. Case 5 was run to determine the effect of replacing U^{235} with Pu^{239}. The indicated result is that the critical mass decreases from 38 to 27 kg.

Table II gives a neutron balance for each case. Since this is a balance of neutrons, and a fixed fraction of neutrons must be absorbed in the fuel, any increase of absorptions in nonfuel regions must be accompanied by a decrease in leakage. One noticeable fact is that even though less fuel is required using Pu^{239}, more neutrons must be absorbed in the fuel. This is due to the larger portion of the neutrons absorbed in the Pu^{239} that do not produce fission neutrons. The decrease in critical mass for Pu^{239} results from the fact that although the probability of a fission per absorption is less than for U^{235}, the probability of an absorption is sufficiently greater to override this effect.

Concluding Remarks

From the two-dimensional calculations performed on cylindrical cavity reactors, it appears that the fuel region can be reduced in radius inside a cavity more than appeared possible from spherical results. The calculations indicate that if graphite is to be required for high temperature use, an increase in critical mass will result, though not as much as would be indicated by the use of room temperature cross sections.

The calculations also show that critical mass can be reduced by using Pu^{239} rather than U^{235}. A single calculation of the effect of a nozzle opening through the reflector-moderator showed only a slight increase in critical mass. Inasmuch as D_2O is a better moderator, it would seem worthwhile to consider a possible combination of D_2O and graphite into a two-region moderator-reflector with high temperature capability and reduced neutron absorptions. Finally, in view of some of the steep flux gradients in a cavity reactor, it is estimated that transport theory would predict, in certain cases, larger critical masses than diffusion theory; this has been indicated by a few preliminary one-dimensional calculations.

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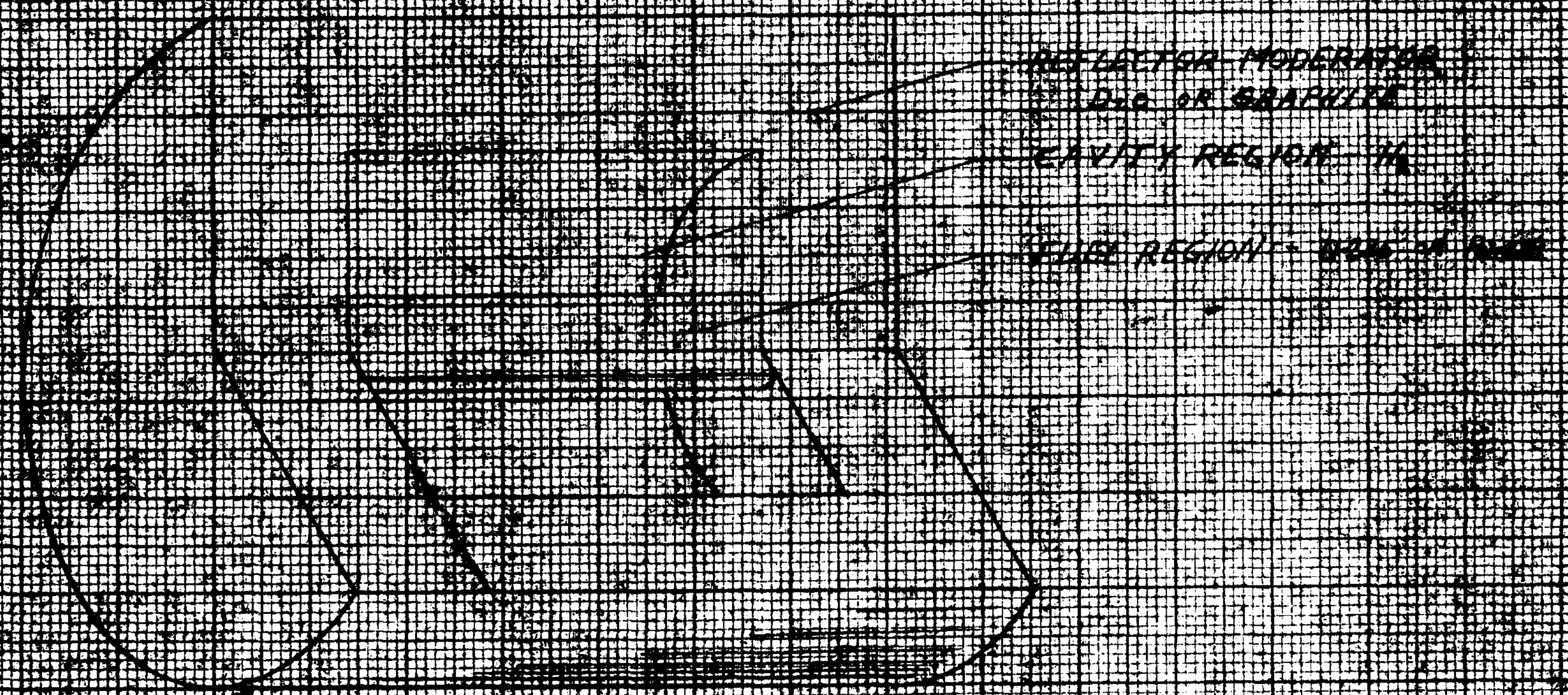

FIG. 1. 2-DIMENSIONAL CAVITY REACTOR MODEL

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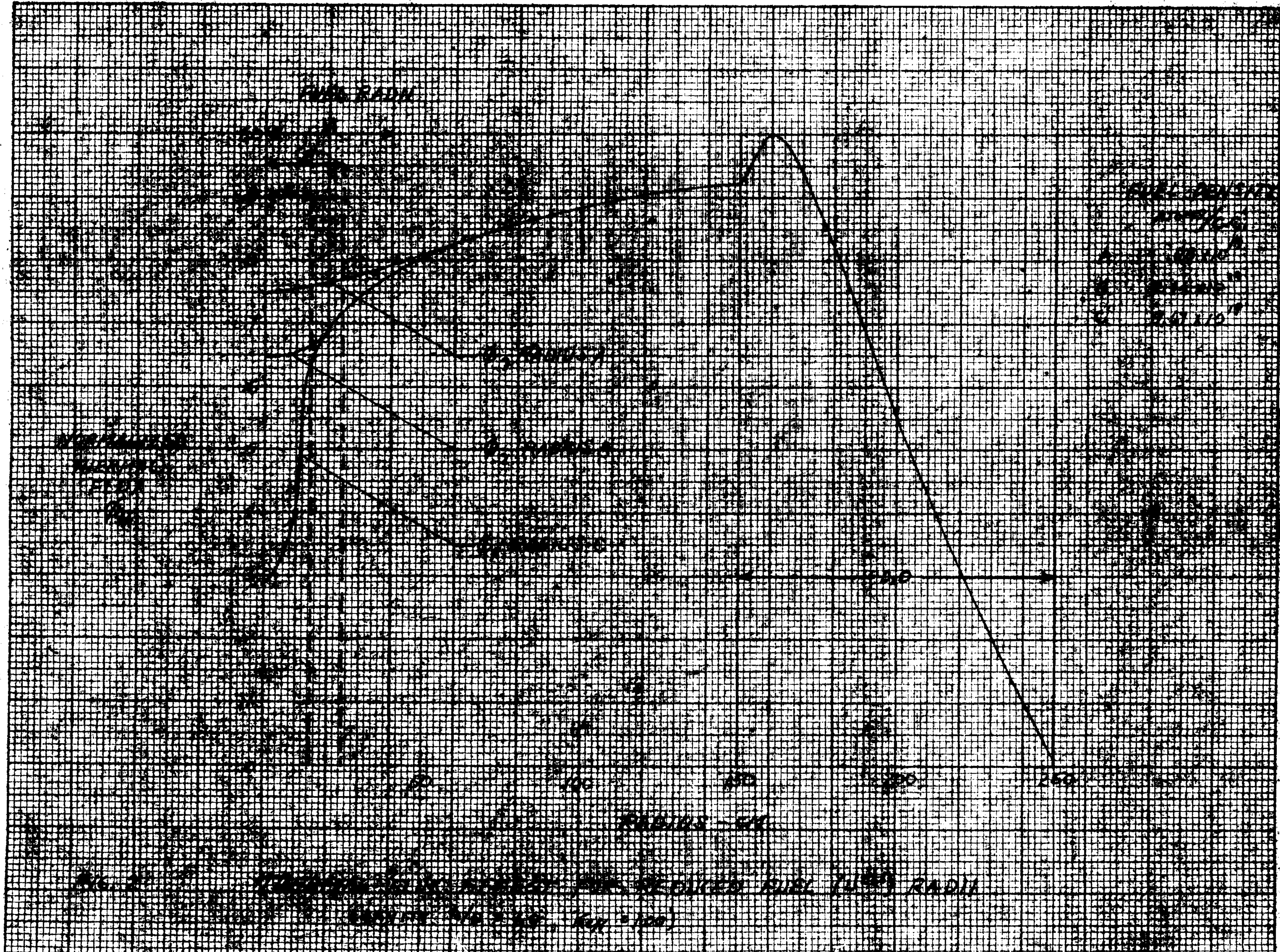
K+E 10 X 10 TO THE ½ INCH KEUFFEL & ESSER CO. 359-12 MADE IN U.S.A.



K+E 10 X 10 TO THE ½ INCH 359-12
KEUFFEL & ESSER CO. MADE IN U.S.A.

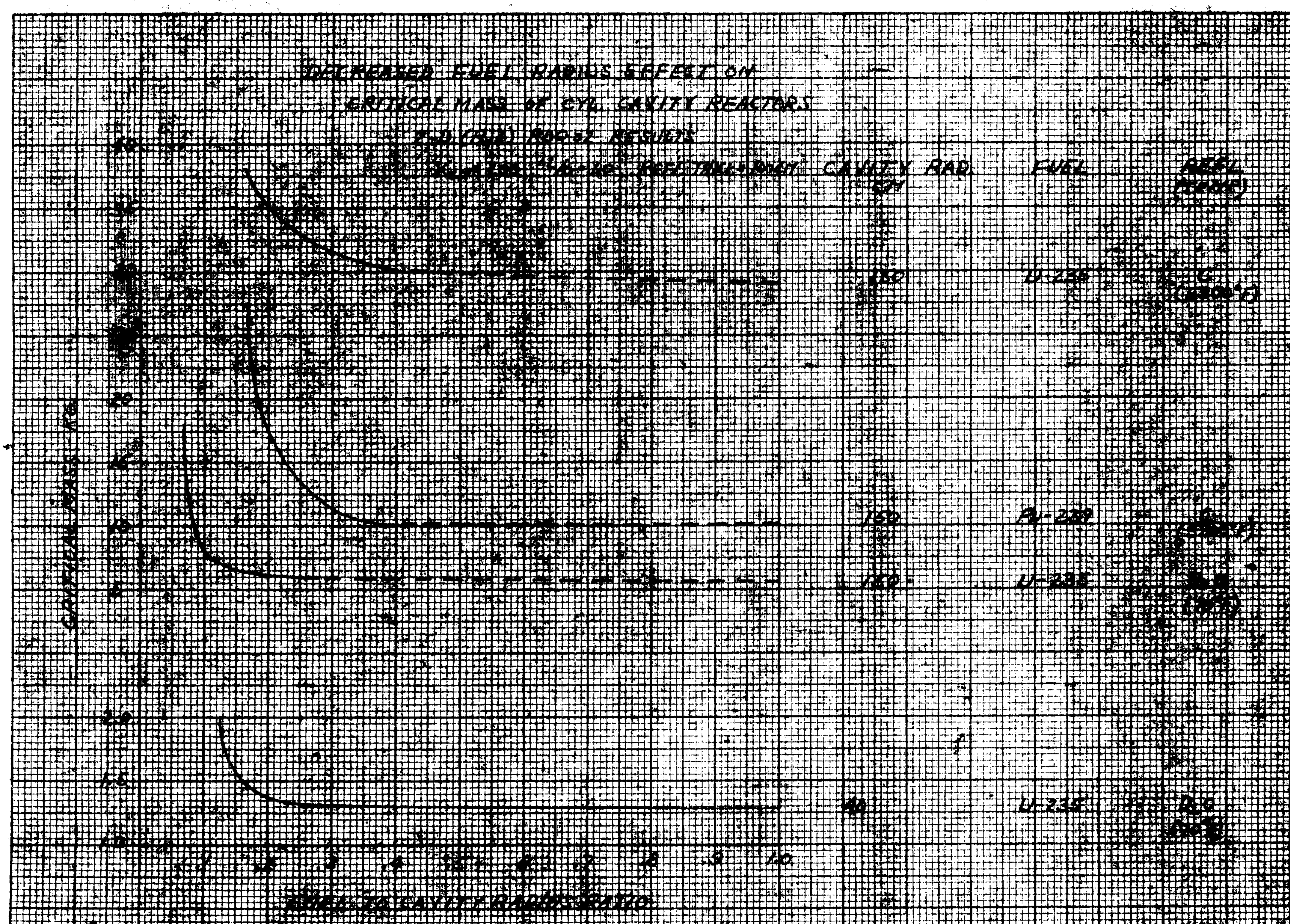


FIG. 3

TABLE I - FUEL INVESTMENTS FOR 2D(R,Z)
DIFFUSION ANALYSIS - CAVITY REACTORS

CASE	REFL.	FUEL-TEMP	NOZZLE	CRITICAL MASS, Kg.
1	D_2O	U-235 [illegible]	NO	14.8
2	D_2O	U-235 [illegible]	YES	6.6
3	C	U-235 [illegible]	NO	15.0
4	C	U-235 [illegible]	NO	38.0
5	C	Pu-239 [illegible]	NO	27.0

REFL. THICK. = 100 CM.
CAVITY L/D = 1.0
CAVITY RADIUS = 100 CM.
FUEL RADIUS = 25 CM.

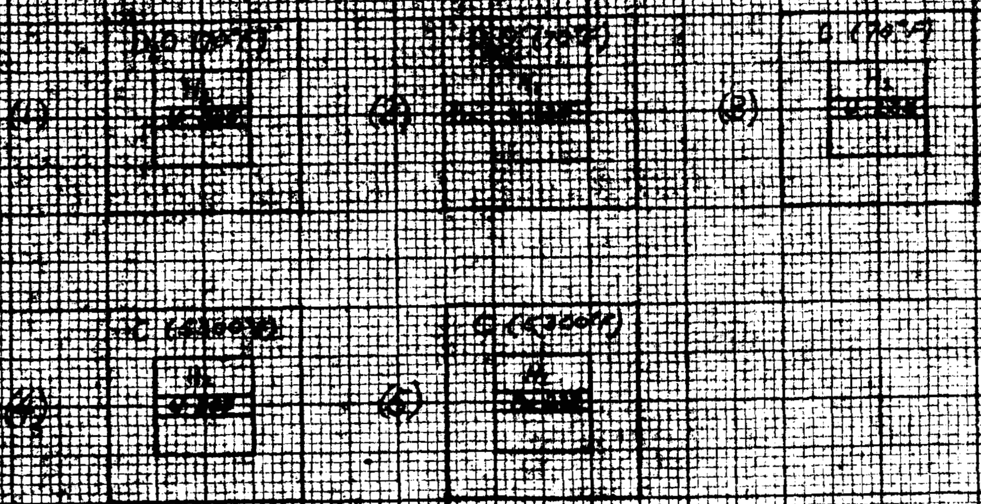


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TABLE II - NEUTRON BALANCES FOR 2-D (R, Z)
DIFFUSION ANALYSIS - CAVITY REACTORS

CASE	[illegible]	FUEL	ABSORPTION FUEL	[illegible]	LEAKAGE	TOTAL
1	[illegible]	U-235	484	67	449	1000
2*	[illegible]	U-235	484	68	448	1000
3	[illegible]	U-235	488	318	194	1000
4	C [illegible]	U-235	482	244	274	1000
5	C [illegible]	Pu-239	552	124	323	1000

* WITH [illegible] NOZZLE

REFL. THICK = [illegible]
CAVITY L/D = [illegible]
CAVITY RADIUS = [illegible]
FUEL RADIUS = [illegible]

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